

cy.7



A SYSTEM FOR THE MEASUREMENT OF VELOCITY DISTRIBUTIONS OF MOLECULAR BEAMS

H. M. Powell and J. H. Heald, Jr.
ARO, Inc.

September 1968

This document has been approved for public release
and sale; its distribution is unlimited.

**AEROSPACE ENVIRONMENTAL FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE**

PROPERTY OF U. S. AIR FORCE
AEDC LIBRARY
F40600-69-C-0001

NOTICES

When U. S. Government drawings specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise, or in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Qualified users may obtain copies of this report from the Defense Documentation Center.

References to named commercial products in this report are not to be considered in any sense as an endorsement of the product by the United States Air Force or the Government.

A SYSTEM FOR THE MEASUREMENT
OF VELOCITY DISTRIBUTIONS
OF MOLECULAR BEAMS

H. M. Powell and J. H. Heald, Jr.
ARO, Inc.

This document has been approved for public release
and sale; its distribution is unlimited.

FOREWORD

The research reported herein was sponsored by Headquarters, Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Program Elements 6144501F and 6540215F, Projects 8951 and 4344, respectively.

The results of the research were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the AEDC, AFSC, under Contract F40600-69-C-0001. The work was conducted from January 1 to December 1, 1967, under ARO Project Nos. SW5701 and SW3811, and the manuscript was submitted for publication on June 17, 1968.

This technical report has been reviewed and is approved.

Burnell B. Algée
Captain, CAF
Research Division
Directorate of Plans
and Technology

Edward R. Feicht
Colonel, USAF
Director of Plans
and Technology

ABSTRACT

A system for determining the velocity distributions of molecular beams is described in this report. This system utilizes the time-of-flight technique whereby the velocities are inferred by measuring the flight time of the beam molecules over a known flight distance. A quadrupole mass spectrometer and signal averaging devices are used to improve the signal-to-noise ratio in such a way that the system is applicable to velocity measurements in an environment of a relatively high background gas density. The system is evaluated by comparison of measured distributions of beams obtained from an effusive source with equivalent calculated Maxwellian distributions. Agreement was good enough that the gas temperature could be calculated from the experimental data by using a least squares computer program. Distributions for beam densities down to 2.7×10^7 molecules/cm³ in a total background of 3.24×10^9 molecules/cm³ were measured. The application of the system to studies involving gas-surface interactions and plume expansion processes from a nozzle is also discussed.

CONTENTS

	<u>Page</u>
ABSTRACT.	iii
NOMENCLATURE.	vi
I. INTRODUCTION	1
II. DESCRIPTION OF TECHNIQUE AND EXPERIMENTAL APPARATUS	
2.1 Time-of-Flight Technique	2
2.2 Experimental Apparatus.	3
2.3 System Alignment.	4
2.4 Preamplifier.	4
2.5 Waveform Educator	5
III. DATA ANALYSIS AND EXPERIMENTAL RESULTS	
3.1 Data Analysis	6
3.2 Performance Evaluation.	7
3.3 Calculated Results	8
IV. SOURCES OF ERROR	
4.1 Time Delays	9
4.2 Distortions Due to Mechanical Effects.	10
4.3 Educator Noise	12
4.4 Time Resolution	12
V. CONCLUSIONS	13
REFERENCES	13

APPENDIX

Illustrations

Figure

1.	Definition of Thermal Accommodation Coefficients . .	17
2.	System Block Diagram for Time-of-Flight Velocity Distribution Detector	18
3.	FET Preamplifier for In-Chamber Operation.	19
4.	Block Diagram of Waveform Educator	20
5.	Typical Educator Input-Output Waveforms	21
6.	Theoretical and Experimental Results for a Maxwellian Velocity Distribution	22
7.	Mass Spectrometric and Total Density Detector Signals.	23

<u>Figure</u>		<u>Page</u>
8.	Ion Flight Times in a Quadrupole Mass Spectrometer.	24
9.	Schematic of Molecular Beam System and Detector Cross Sections	25
10.	Several Chopper Shutter Functions for Fixed Rotational Speed	26
11.	Velocity Distributions for High Temperatures	27

NOMENCLATURE

A	Area of collimator
D	Chopper wheel diameter
D_b	Gas density due to background gases
D_c	Composite gas density due to background and chopped beam gases
D_n	Normalized gas density
D_q	Quadrupole delay time
D_v	Gas density due to chopped beam component
d_a	Ionizer entrance aperture cross section
d_e	Effective beam cross section
d_i	Ionizer electron beam cross section
$d\omega$	Element of solid angle of the collimator in relation to source orifice
E_i	Mean translational energy of an incident beam
E_q	Energy of quadrupole ion beam
E_r	Mean translational energy of scattered molecules
E_s	Energy of completely accommodated molecule equivalent to target temperature
f	Flight distance
k	Boltzmann constant
ℓ	Gas orifice-collimator separation

m	Molecular mass
n_0	Total number density of gas molecules in beam source
p_0	Source pressure
S	Chopper rotational speed
T	Temperature, °K
T_i	Temperature of incident beam
T_r	Temperature of scattered beam
T_s	Temperature of target
t	Time
t_f	Flight time
t_0	Reference time zero of theoretical Maxwellian distribution
t'_0	Reference time zero of experimental distribution
t_s	Eductor sweep time
V_b	Equivalent signal level of background gases
V_c	Equivalent composite signal due to background and chopped beam
V_n	Equivalent eductor noise
V_t	Signal of timing component, synchronous pulse
V_v	Equivalent signal of chopped beam component
v	Velocity
w	Chopper slit width
α	Accommodation coefficient
τ	Width of shutter function when slit width and effective beam cross section are equal

SECTION I INTRODUCTION

Several research programs conducted in the Aerospace Environmental Facility in recent months have established a need for a device to measure the velocity distributions of molecular flow in vacuum environments. However, direct application of previously developed techniques does not completely meet the present needs. This limitation, as will be described, is based upon the relative density of the background gases.

The measurements of velocity distributions generally have previously used the time-of-flight technique. The velocity is not measured directly but is inferred by determining the particle flight time over some known flight distance. Scott, J. E., et al. (Ref. 1); Anderson and Fenn (Ref. 2), Scott, P. B., et al. (Ref. 3), and Marcus and McFee (Ref. 4), among others, have been instrumental in the development of the time-of-flight technique. Most of these systems use a single chopper wheel and monitor the time-dependent density at a detector with a specified separation or use a velocity selector with two or more chopper wheels. The detectors for these and other systems use ion gages sensitive to total gas densities except in those cases where surface-ionization detectors are used with potassium or cesium beams. Detectors that are sensitive to total gas density have difficulty in recovering a signal that is deeply imbedded in noise. The source of this noise is the background molecules of multiple-gas species that are randomly ionized and detected. Scott (Ref. 3) was instrumental in devising a signal averaging scheme to reduce the effect of this noise in the output media.

The system considered here is in most respects similar to other systems using the single chopper wheel approach but has variations in the detector scheme to improve the sensitivity for signals in high background noise. Commercial instruments have been marketed that readily enhance the signal-to-noise ratio. These instruments, normally referred to as waveform ~~eductors~~, ~~are used~~ in the system discussed here. Because of the sensitivity requirement, an effort was also made to reduce the system noise further through the use of a mass spectrometer. Earlier experiments utilized simple ionization gages as a detector for studying high intensity beams. Ion gage output current is proportional to the ionization of all constituents, whereas the mass spectrometer output depends on the mass discrimination of its filter section. The output current is the test gas ion current only; therefore, most of the contributors to the background noise are eliminated. Of particular interest here is the use of the spectrometer and the waveform ~~eductor~~ and the part they play in recovering weak signals. For the most part, all items are commercially available components.

The specific applications to present needs are certain studies concerned with gas-surface interactions and jet plume mapping of rocket exhausts. However, the approach is general enough for many other applications, one of which is studying flow fields where the velocity distribution at some specific location may be obtained by collimation of the flow ahead of the system detector.

Specifically, in the general field of gas-surface interactions, the degree to which gas particles attain thermal equilibrium with the surface is of fundamental importance. A thermal or energy accommodation coefficient is useful in expressing this degree of energy exchange.

$$\alpha = \frac{E_i - E_r}{E_i - E_s} \quad (1)$$

The nature of the gas-surface interaction experiments for determining α is shown in Fig. 1 (Appendix). With a molecular beam incident upon a target of known temperature T_s , E_i represents the mean translational energies of the incident beam, E_r represents the mean translational energies of the scattered molecules, and E_s is the value which E_r would have if the particles were completely accommodated. In a molecular beam experiment, the measurement of the translational speed distribution of the incident and reflected gas molecules can be used to make a direct calculation of the thermal accommodation coefficient.

One difficult aspect of testing rockets in a simulated space environment is maintaining vacuum conditions during rocket firings. This problem could be greatly alleviated if rockets with thrust levels lower than the full-scale rocket could be tested. This would require the use of adequate scaling laws to properly interpret the results using these scaled-down thrusters. Also, the proper interpretation of any measurements made within the rocket plume, such as force measurements on a test surface, would require knowledge of the gas-dynamic state of the rocket plume. For these purposes, velocity distribution measurements could provide the necessary gas-dynamic description of rocket exhaust plumes. To utilize this technique for rocket exhaust plume measurements, the system must be sufficiently small and lightweight for mounting inside a scanning probe.

SECTION II

DESCRIPTION OF TECHNIQUE AND EXPERIMENTAL APPARATUS

2.1 TIME-OF-FLIGHT TECHNIQUE

Figure 2 is a block diagram of the complete system. The principle of operation is as follows. The beam passes through the slits of the

chopper wheel, giving an approximate impulse function of molecules. As time elapses, these molecules spread according to their respective velocities. Their arrival time at the detector ion source is inversely related to the velocity. Thus, the spectrometer output is a time-dependent function of the local density in the ion source.

2.2 EXPERIMENTAL APPARATUS

2.2.1 Description of Calibration Chamber

To properly evaluate the results, the system must be calibrated against a beam with a known distribution. The beam generator of Fig. 2 produces a molecular beam of known intensity (molecules/sec-cm²) and velocity distribution. The test gas originates in a small gas plenum at a sufficiently low pressure to ensure random, free molecular flow through a thin-walled orifice into a surrounding vacuum. The criterion used to ensure free molecular flow is that the source Knudsen number should be greater than unity. Knudsen number is defined as the ratio of the source gas mean free path to the source orifice diameter. This criterion ensures a known velocity distribution of the Maxwell-Boltzmann type. The plenum is platinum tubing, which also acts as a heater element for experiments involving distribution measurement of hot gases. A beam is formed by those molecules passing through a collimating orifice located in the dividing wall between the two vacuum chambers.

2.2.2 Description of the Time-of-Flight Detector

A 4-in. -diam, aluminum chopper wheel was used with two 70-mil knife-edge slots. The dimensions and number of slots depend on the relative flight time, beam diameter, dimensions of ionization region and desired data acquisition time. The beam chopper was driven by a small, two-phase synchronous motor. This is a 115-v, 400-Hz, 24,000-rpm motor with a vacuum rating. A tunable oscillator and slave were used for speed control. A light and sensor were mounted directly opposite the beam and served as both a timing reference and a synchronizing pulse for the waveform eductor triggering.

The output of the ion source depends on the density of all the background gas, as well as the test gas. However, with a mass spectrometer tuned for the transmission of only the test gas, most constituents of the ion source output are essentially rejected. The background test gas appears as random noise at the detector output since it does not have any coherent components with the frequency of the chopper wheel.

These random components are removed by the waveform eductor after preamplification, but those signals coherent with chopper rotation are retained. This includes the time-of-flight distribution, as well as the stray signals from the motor drive circuits.

2.3 SYSTEM ALIGNMENT

To assure the integrity of the results, considerable care must be given to the system alignment. To establish a precise reference for time zero, the system must not be sensitive to rotational direction, i.e., adequate alignment requires that the beam aperture and light aperture to the synchronous pulse sensor be fully open at the same time. This condition is obtained by using a laser beam directed along the molecular beam centerline and incident upon a photocell in the collimating orifice. The chopper lateral alignment is assured when the synchronous pulse and the pulse obtained from the chopped laser beam are coincident in time. The alignment must also assure that the system is not sensitive to multiple possibilities of ionization after the beam once passes through the ionizer electron beam. This problem merely requires careful optical alignment of the quadrupole centerline with the molecular beam centerline. Collisions with aperture plates internal to the ionizer are eliminated by reducing the molecular beam entrance aperture to a diameter less than the smallest ionizer aperture. If a beam molecule does return to the ionization region, multiple collisions outside this region ensure that it has lost all its history with respect to its original dynamic state, and it appears in the output as background gas.

2.4 PREAMPLIFIER

Essential to the operation of the system is the use of some type of buffer between the spectrometer multiplier output and the amplifier input. In the interest of sensitivity, the multiplier load impedance must be large. However, this is not compatible with the capacitive loading as a result of cable shielding and the required overall frequency response of the system. In the present application a field effect transistor (FET) type of emitter-follower circuit was used (Fig. 3). The requirements of high amplifier input impedance for good signal levels at the multiplier output and low source impedance for driving coaxial lines are met with this device. This circuit is mounted directly on the quadrupole tube inside the vacuum chamber. A synchronous pulse is added to the spectrometer signal, as shown in Fig. 2, so that a time reference may be retained along with the distribution. This is done by utilizing

the differential input feature of the preamplifier. Thus, a composite waveform is obtained with flight times taken with respect to the synchronous pulse.

2.5 WAVEFORM EDUCATOR

Figure 4 is a basic block diagram of the educator. The signal which consists of the distribution function plus the noise of the background gas may be amplified further at the educator input. This composite signal is fed through one of several resistors onto a signal bus common to a bank of 100 memory capacitors. These capacitors are connected to the signal bus through an insulated gate-type FET. A precisely timed internal clock oscillator, which is externally triggered by the chopper synchronous pulse, advances a ring counter which controls the memory gates. These gates close and open consecutively, and each of the memory capacitors in turn is tied to the signal bus. Since the sweeps are synchronized with the chopper rotation and the flight time of the gated molecular beam, the distribution will gradually be stored in the memory. The same portion of the distribution function is applied to any given capacitor on successive sweeps. Since the signal is being integrated as a result of the selected time constant, the noise is suppressed. The capacitors are also connected to a high-input impedance amplifier for isolation from the output terminations. Provision is made for "erasing" the memory and for "delayed" nondestructive readout of the memory at speeds completely independent of those used to store the waveform. Three output devices were used: (1) an oscilloscope to observe the status of data acquisition, (2) an X-Y recorder for permanent record, and (3) a data logger for entry into a computer for data reduction purposes.

SECTION III DATA ANALYSIS AND EXPERIMENTAL RESULTS

To evaluate the performance of the detector system, the measured time-of-flight distributions have been compared with theoretical distributions calculated from the Maxwell-Boltzmann velocity distribution function.

3.1 DATA ANALYSIS

If the gas molecules in a beam source container have a Maxwellian velocity distribution, the number per unit volume with a speed v is

$$dn_v = \frac{n_0}{\pi^{3/2}} \left(\frac{2kT}{m} \right)^{-3/2} v^2 \exp\left(\frac{-mv^2}{2kT}\right) dv \quad (2)$$

The kinetic theory relation for the number of molecules with speed v striking the surface of a container per unit area and per unit time is

$$dI_v = \frac{1}{4} v dn_v \quad (3)$$

Substituting Eq. (3) into Eq. (2) gives the number of molecules with speed v striking the walls of the beam source container per unit area:

$$dI_v = \frac{n_0}{\pi^{3/2}} \beta^3 v^3 \exp(-\beta^2 v^2) dv \quad (4)$$

where β has been substituted for the term $\left(\frac{2kT}{m}\right)^{-1/2}$.

If the orifice in the beam source container is sufficiently small to ensure free molecular effusive flow through the orifice into the surrounding vacuum, then the cosine distribution law can be used to calculate the molecular beam intensity passing through a collimator orifice located downstream of the source orifice:

$$(dI_v)_c = dI_v \frac{\cos \theta}{\pi} d\omega \quad (5)$$

If the collimator is located on the axis of the source orifice, then $\theta = 0$ deg $\cos \theta = 1$. If the diameter of the collimator is small in comparison with the separation distance between source orifice and collimator, then $d\omega = \frac{A}{\ell^2}$. Equation (5) can then be used in Eq. (4) to write

the speed distribution function for molecules passing through the collimator:

$$\frac{(dI_v)_c}{dv} = \frac{n_0 A}{\pi^{3/2} \ell^2} \beta^3 v^3 \exp(-\beta^2 v^2) \quad (6)$$

The distributions measured by the time-of-flight detector will be in terms of flow density through the ionization region of the mass spectrometer versus flight time between chopper wheel and mass spectrometer. Therefore, the distribution function, Eq. (6), must be transformed from intensity versus speed coordinates to density versus time coordinates. The flight time is simply

$$t_f = \frac{\ell}{v} \quad (7)$$

which gives

$$dv = \frac{f}{t_f^2} dt_f \quad (8)$$

The flow density is related to the beam intensity by the flow velocity,

$$(dl_v)_c = v(dn_v)_c \quad (9)$$

Substituting Eqs. (7) through (9) into Eq. (6) gives the number density in the mass spectrometer ionization region at a flight time t_f :

$$\frac{dn_v}{dt_f} = \frac{A n_o}{\pi^{3/2} t_f^2} \beta^2 \frac{f^3}{t_f^4} \exp\left(-\beta^2 \frac{f^2}{t_f^2}\right) \quad (10)$$

Equation (10) has been utilized to calculate the theoretical distribution of molecular density at the detector as a function of source temperature and flight distance.

3.2 PERFORMANCE EVALUATION

The experimental arrangement for the system evaluation utilized the calibration chamber described earlier (Section 2.2.1). Nitrogen and argon were used for the test gases. The quadrupole spectrometer was mounted with its axial centerline coinciding with that of the molecular beam, as shown in Fig. 2. The quadrupole was operated normally and with manual mass control preset for the test gas of interest. With a typical distribution, the slowest possible chopper speed was selected according to a criterion to be described later. Actual calibration runs used a plenum source pressure to ensure a known Maxwell-Boltzmann distribution in the molecular beam.

Shown in Fig. 5 are typical oscilloscope waveforms obtained with the present system. The first trace shows the output of the waveform eductor and the second, the spectrometer input before signal averaging. The need for waveform enhancement is obvious. Most of the experiments were run in the range from 1 to 4×10^{-7} torr. However, considerably higher pressures could be tolerated, provided the test gas was not a high percentage of background gas.

As indicated earlier, the eductor has capabilities of recording at lower sweep speeds. Shown in Fig. 6 are the results of one such recording of a distribution function. The recorded results appear as a sequence of 100 steps on plateaus, each step representing an amplitude of the stored charge of the 100 memory capacitors in the waveform eductor. To demonstrate the validity of the data recorded by

the waveform eductor, the results are compared with a Maxwellian distribution which was calculated using Eq. (10) and plotted as a series of circles in Fig. 6. The experimental data are for a source Knudsen number of one. The calculated results fall within the scatter of the experimental results. This is equivalent to a density of 10^8 molecules/cm³. Under conditions of good sensitivity and alignment, distributions for beam densities down to 2.7×10^7 molecules/cm³ have also been obtained. These measurements were made with a 3/16-in. entrance aperture and in a background pressure corresponding to about 3.24×10^9 molecules/cm³. These beam densities correspond to the density of scattered molecular beams anticipated in experiments to be used in the determination of thermal accommodation coefficients. As would be expected, the ultimate sensitivity depends on background pressure of the test gas species.

The advantage in using a mass spectrometer in preference to other detectors is inferred in Fig. 7. This figure shows the results for a fixed-beam intensity with two different detector arrangements. The first is sensitive to several background gases adjacent in mass number to the test gas, and the other is sensitive only to the test gas; the advantage is obvious.

3.3 CALCULATED RESULTS

As indicated earlier, one of the applications is for the determination of accommodation coefficients. If the velocity or temperature of molecules reflected from a cold surface can be inferred from the distribution, this accommodation coefficient can be determined. Even with a system time delay, which is to be discussed later, the shape of the distribution is adequate to give good results when calculating gas temperatures.

A least squares program was used to fit experimental data from an effusive source to a Maxwellian distribution. Since a time delay was involved in the experimental data, the curve fit was based upon the shape of the distribution curve only. The basic idea of this program was to shift the experimental data until the residue (sum of square of the errors) between corresponding experimental and theoretical points of a least squares fit was minimized. Utilizing this approach, temperatures with no greater than 3°K error at room temperature were obtained. This represented the worst fit for several runs made with the same beam intensity.

Distributions of high temperature beams were also used for evaluation purposes. By resistance heating of the gas plenum, beam temperatures to 1500°K could be obtained. When comparison is made with the plenum thermocouple data, the calculated beam temperature using the most probable flight time agreed to within 50°K.

SECTION IV SOURCES OF ERROR

The experimental results suggest that the measured shapes of the distribution functions are correct. In all cases the evaluation was based upon the assumed existence of free molecular flow through the orifice. A source Knudsen number of one gives a small deficiency in molecules of the slower velocities. This effect, however, can be reduced by going to lower source pressures. It is more thoroughly discussed by Scott (Ref. 3).

There is an error in the flight times which systematically makes all intensities appear slower than they actually are. The effect is a shift of the reference point from which time $t = 0$ must be taken. These and other sources of error are discussed below.

4.1 TIME DELAYS

4.1.1 Amplifier Frequency Response

Consideration must be given to the bandwidth and frequency response of the amplifier circuits. Amplifier gains generally are fairly constant except at frequencies greater than the bandwidth. However, a lagging phase shift becomes significant at higher frequencies. Therefore, the overall frequency response must be adequate to reduce the phase shift to a tolerable amount. As evidence of this effect, there is a lag or time delay in the measured distribution, whereas the shape is apparently correct. This shift makes the velocities appear slower than they actually are. Experience in the present system required a compromise in sensitivity and bandwidth at the input of the FET buffer. A 150-kc bandwidth was maintained in present experiments and appears to be adequate for most applications.

4.1.2 Quadrupole Flight Times

The most serious time delay occurs in the actual ion flight time through the quadrupole ion source and mass filter section. Maximum spectrometer sensitivity occurs with approximately 22 v of ion energy. For argon this amounts to 28 μ sec through the mass filter section. The response time of the multiplier is essentially insignificant when compared with these flight times. This delay must be known for all gases intended for experimental use if direct calculations of velocities are required. Because of the character of the ion source design and the method of measurement, these quadrupole flight times do not vary as the inverse square root of the ion energies. Figure 8 shows how quadrupole flight times vary with mass number and ion energy.

The quadrupole flight times were measured by gating the ion beam with a 5- μ sec pulse at the focus aperture of the ion source. This pulse was also used as a sweep trigger and as an input to a dual-beam oscilloscope. The amplifier output was simultaneously applied to the second oscilloscope beam, and the pulse separation of the two beams was measured. This separation gave the total delay through the system. A family of curves for the quadrupole delay time is shown in Fig. 8.

4.2 DISTORTIONS DUE TO MECHANICAL EFFECTS

There are several interrelated factors that can contribute to the shape of the distribution distortion. These are flight distance, beam width, slit width, rotational speed, size of quadrupole entrance aperture, and effective cross section of electron beam. The interrelationship of these parameters may be seen in Fig. 9. These distortion effects are essentially due to fast molecules reaching some portion of the ionization region during the same time interval that earlier gated, slower molecules are being ionized. For example, a slow molecule that passes through the chopper just as it opens to the beam can reach the ionizer at the same time as a faster molecule that passes through the chopper just before it is closed to the beam.

4.2.1 Effective Beam Cross Section

The effective beam cross section is that portion of the molecular beam referred to the chopper location which is subject to ionization upon entering the ion source. As seen in Fig. 9, several items contribute to the effective beam cross section. Generally, the dimensions of each will be established by criteria other than those of the instrumentation systems. The effective beam cross section is important to

the extent that it can partially determine the time that the beam is open at the chopper. In the present case the beam width is determined by the smallest aperture cross section internal to the ionizer. The entrance aperture must be smaller to ensure that there is no scattering within the ionizer.

4.2.2 Chopper Slit Width

The shutter function is the spatial- or time-dependent function of that portion of the molecular flux that is open to the quadrupole ionizer (Fig. 10). For simplicity, a rectangular beam cross section has been assumed. The independent variable may be either time or displacement if the rotational speed is assumed the same for each case. The entire beam flux of the effective beam cross section passes through the chopper wheel when the shutter function is 1.0. The triangular shutter function corresponds to a slit width the same as the effective beam cross section. The trapezoidal functions denoted a and c correspond to a slit width greater and less than the effective beam cross section, respectively.

Ideally, the shutter function should be as short as possible to effectively represent a true impulse function. An impulse function represents a limiting case. From Fig. 10 it may be seen that nothing can be gained by reducing the slit width to less than the effective beam cross section, for beyond this point the transmission suffers without improvement in the rise time.

4.2.3 Chopper Rotational Speed and Flight Distance

The necessary chopper rotational speed for valid results is related to the particle flight time. Assuming equal slit width and effective beam cross section, if the ratio of τ , the time duration of the shutter function, to the flight time is less than 0.05, generally data without serious distortion (distribution widening) are obtained. The usual approach is to use the slowest rotational speed above which any increase in rotational speed does not change the distribution. If these criteria cannot be obtained, consideration must be given to the possibility of reducing the slit width and/or increasing the flight distance. These approaches should be optimized in terms of the decrease in sensitivity of the system.

4.2.4 Electron Beam Cross Section

A secondary consideration should be the electron beam cross section denoted as d_i in Fig. 9. This distance should be as small as possible.

The implication is that particles of two different velocities could be simultaneously ionized as they enter or leave the electron beam cross section.

4.3 EDUCTOR NOISE

Another source of error, eductor internal noise, can be a limiting factor in the sensitivity of the system. The predominant internal "noise" in the eductor arises because the field effect transistor gates, which control the memory capacitors, vary somewhat in their junction capacitance. As a result the memory capacitors, over a large number of sweeps, become slightly charged, each to a different level, and it is this false memory content which constitutes the eductor noise. This noise is directly proportional to the characteristic time constant and inversely proportional to the sweep time. This noise, to a degree, is repeatable so that better results can be obtained by recording the spectrometer output with the molecular beam off and subtracting this from the distribution recording. This also will remove those extraneous coherent components associated with the motor and the motor drive circuits. Distributions with this correction are shown in Fig. 11, and a comparison with Fig. 6 shows the relative improvement. Figure 11 shows distributions obtained for two temperatures and a comparison with the known theoretical Maxwellian distribution. Reference time zero for the experimental results is indicated as t'_0 , whereas t_0 is reference time zero for the Maxwellian distribution. The interval between t_0 and t'_0 is the quadrupole delay time discussed earlier (Section 4.1.2).

4.4 TIME RESOLUTION

For some applications, the flight time may become long when compared with the actual width of the distribution function. This, in normal application of the eductor, would result in only a few of the possible 100 eductor samples defining the actual distribution function. This could result from situations involving the study of very narrow velocity distribution functions. An adjustable time delay is available whereby any fixed delay after the synchronous pulse may be obtained, and the actual sampling begins at the end of this delay. The eductor sweep would then be the time of the actual distribution function itself.

SECTION V CONCLUSIONS

An improved system for the measurement of velocity distributions of molecular beams has been developed and evaluated. It is based on the time-of-flight technique and is assembled, for the most part, with commercially available components. This system has improved signal-to-noise characteristics over earlier systems by using mass spectrometer techniques and signal-averaging devices.

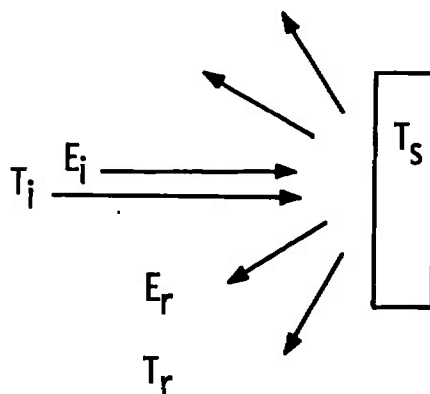
The velocity distribution of low-intensity molecular beams has been measured. Good agreement with the theory for Maxwellian distributions of an effusive flow has been obtained, and the error can be adequately accounted for. The system developed has also been used with good results in measuring the velocity distribution of beams with temperatures from 300 to 1500°K. The results of this investigation have also indicated the feasibility of determining the temperature of a molecular beam using a least squares fit of the experimental data to the known theoretical distribution.

The system is unique in that it is applicable to situations involving relatively high background gas densities. Applications of particular interest are plume mapping of a high temperature expansion process from a rocket nozzle and measurement of accommodation coefficients in gas-surface interaction studies.

REFERENCES

1. Scott, J. E., Jr., Morton, H. S., Jr., Phipps, J. A. and Moonan, J. F. "Distribution Function Measurements in Rarefied Gas Flow through an Orifice." Project SQUID Technical Report UVA-5-P, July 1964.
2. Anderson, J. B. and Fenn, J. B. "Velocity Distributions in Molecular Beams from Nozzle Sources." The Physics of Fluids, Vol. 8, No. 5, May 1965, pp. 780-787.
3. Scott, P. B., Bauer, P. H., Wachman, H. V. and Trilling, L. "Velocity Distribution Measurements by a Sensitive Time of Flight Method." Fifth International Symposium on Rarefied Gas Dynamics, Vol. II, Academic Press, New York, 1967.
4. Marcus, P. M. and McFee, J. H. "Velocity Distributions in Potassium Molecular Beams." Recent Research in Molecular Beams, Academic Press, New York, 1959.

**APPENDIX
ILLUSTRATIONS**



$$\alpha = \frac{E_i - E_r}{E_i - E_s}$$

E_i - MEAN TRANSLATIONAL ENERGIES OF INCIDENT MOLECULES

E_r - MEAN TRANSLATIONAL ENERGIES OF SCATTERED MOLECULES

E_s - VALUE WHICH E_r WOULD HAVE IF THE PARTICLES WERE COMPLETELY ACCOMMODATED

Fig. 1 Definition of Thermal Accommodation Coefficients

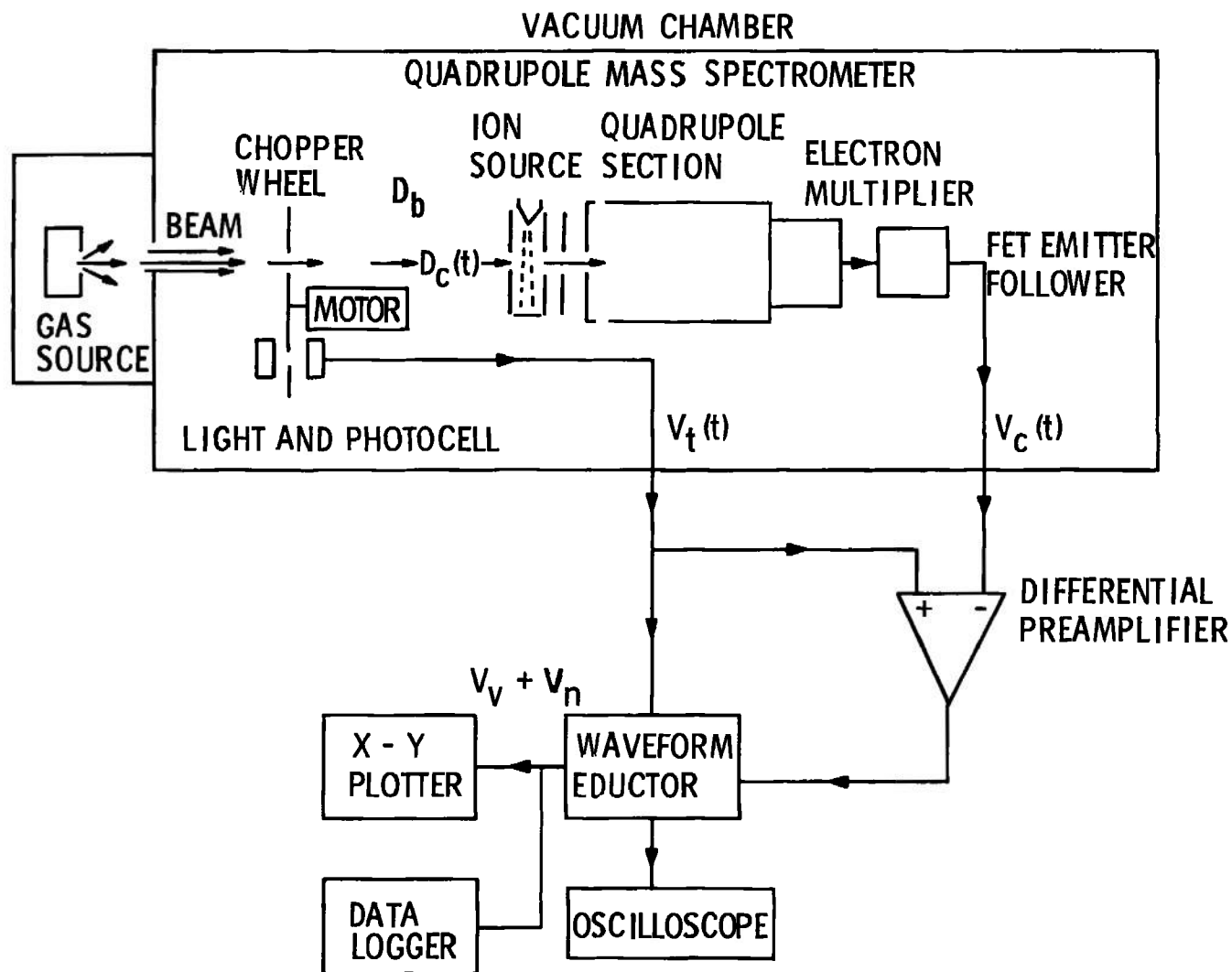


Fig. 2 System Block Diagram for Time-of-Flight Velocity Distribution Detector

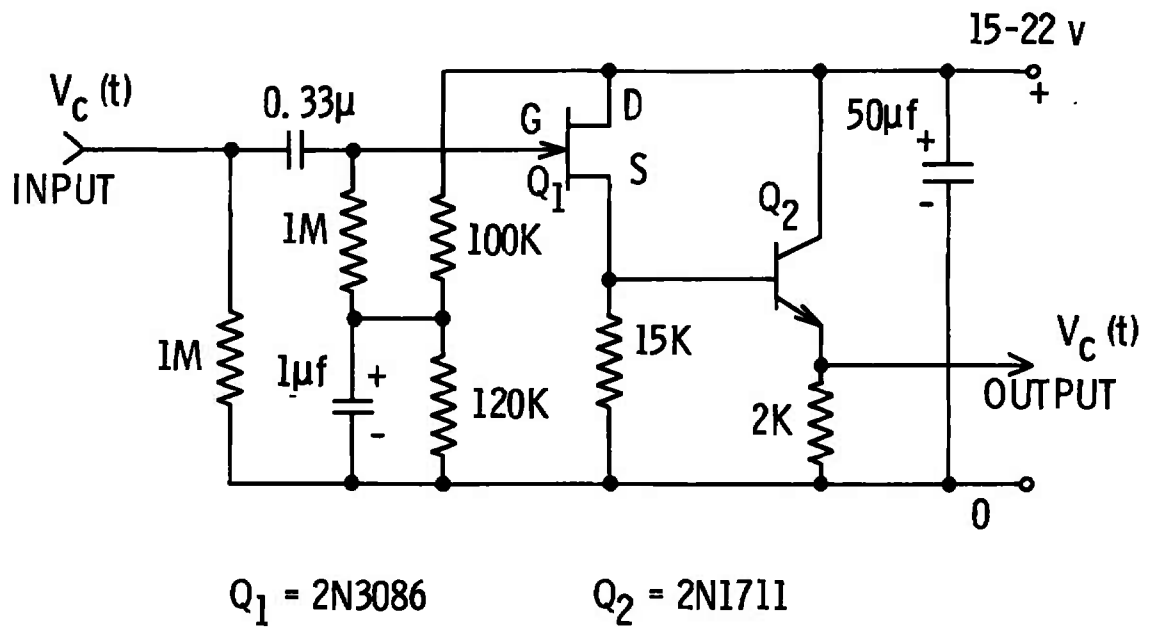


Fig. 3 FET Preamplifier for In-Chamber Operation

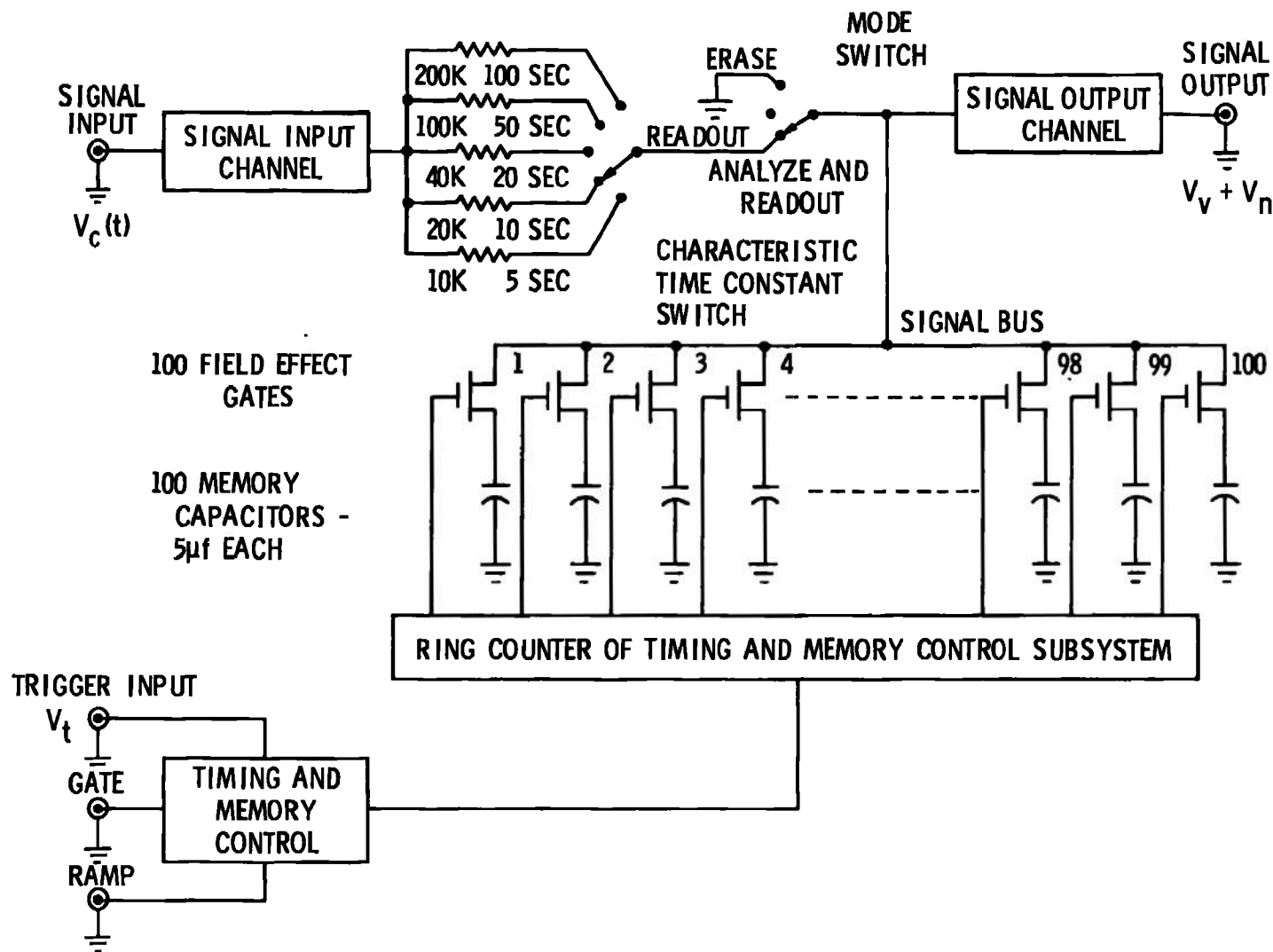
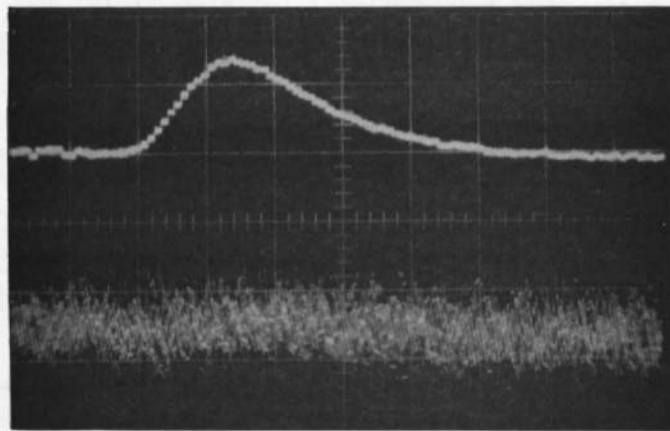


Fig. 4 Block Diagram of Waveform Educator



OUTPUT
 $V_v + V_n$

INPUT
 $V_c(t)$

NITROGEN - ROOM TEMPERATURE
SWEEP TIME - $750 \mu\text{SEC}$
FLIGHT DISTANCE - 3.95 IN.

Fig. 5 Typical Eductor Input-Output Waveforms

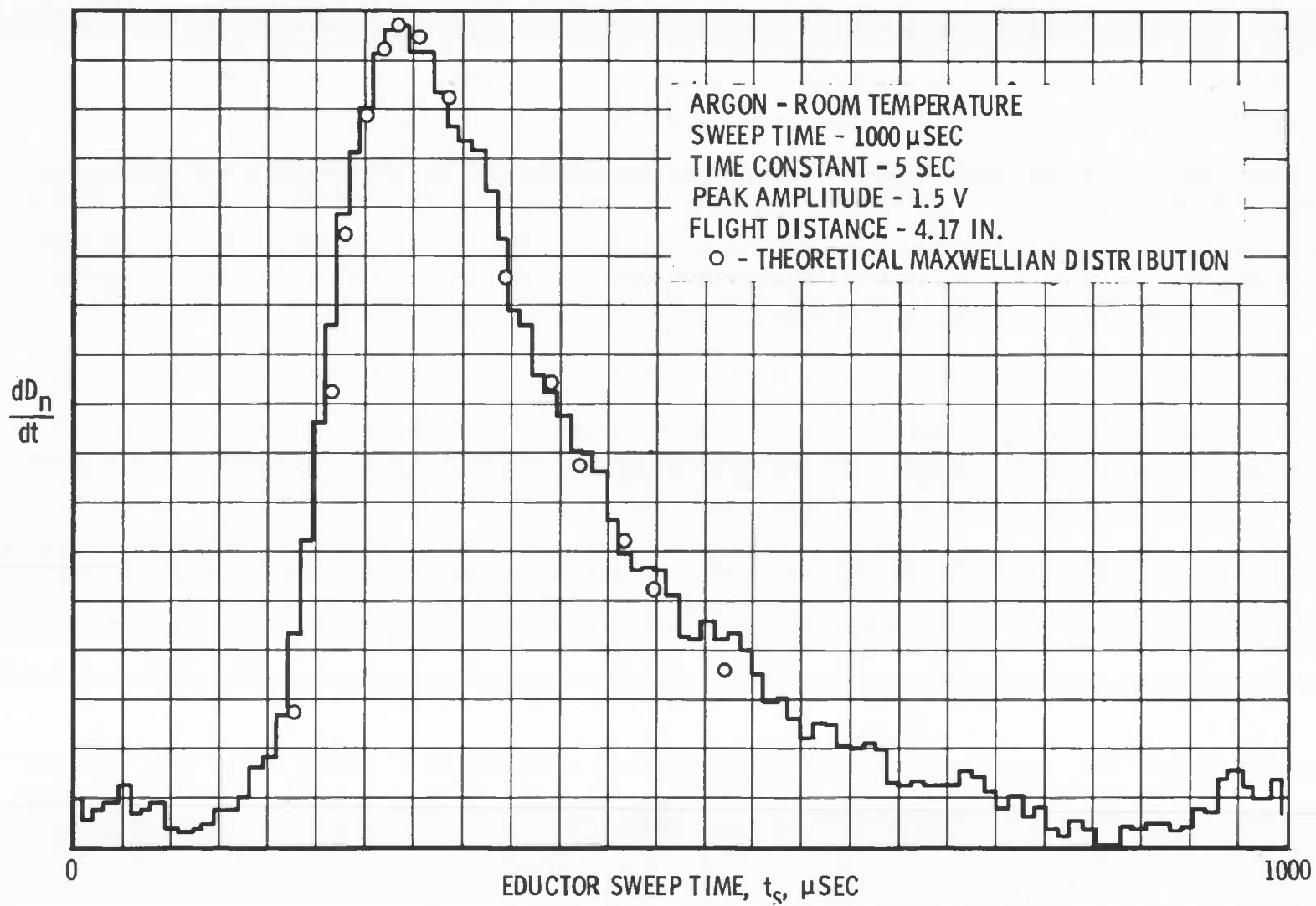


Fig. 6 Theoretical and Experimental Results for a Maxwellian Velocity Distribution

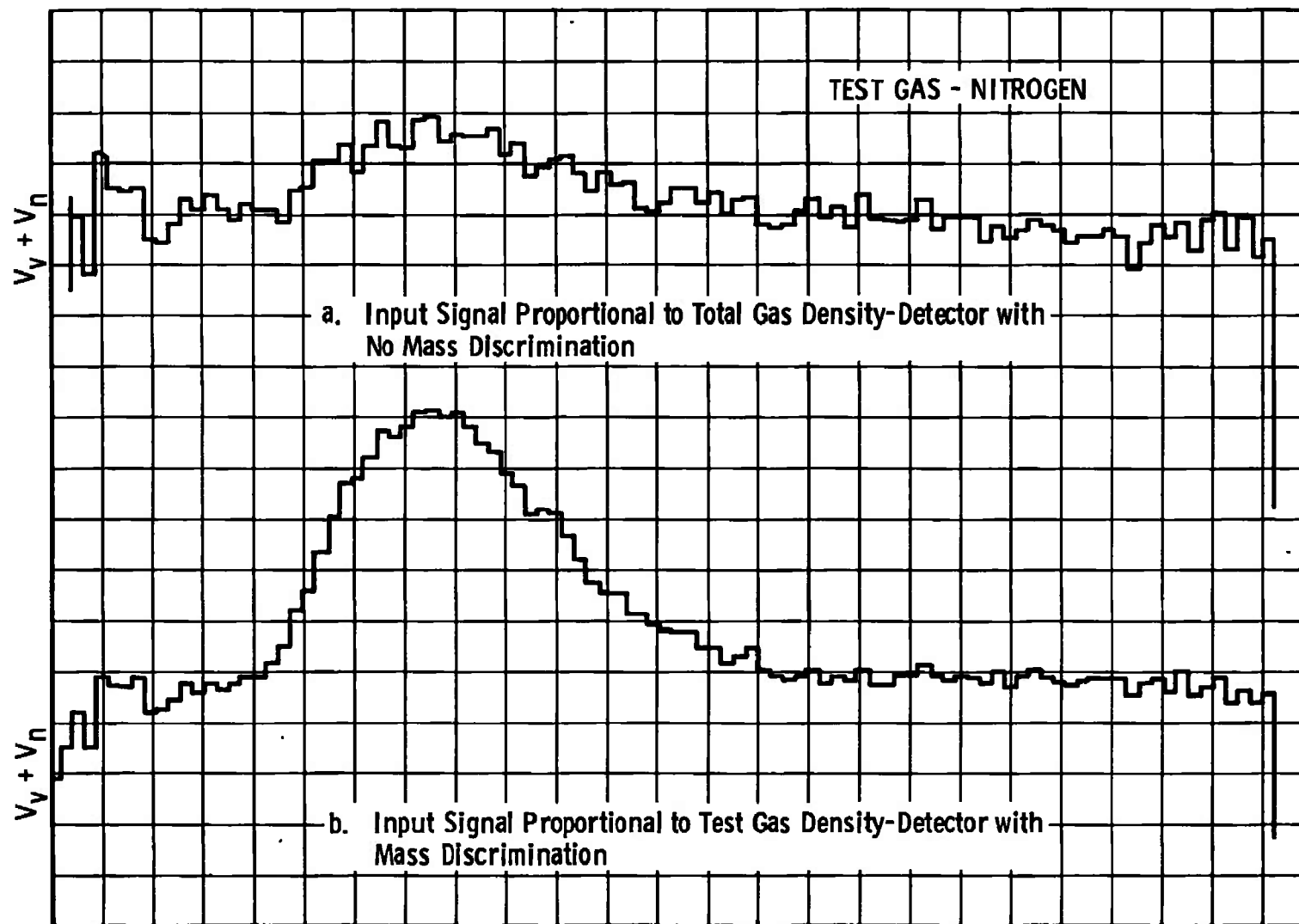


Fig. 7 Mass Spectrometric and Total Density Detector Signals

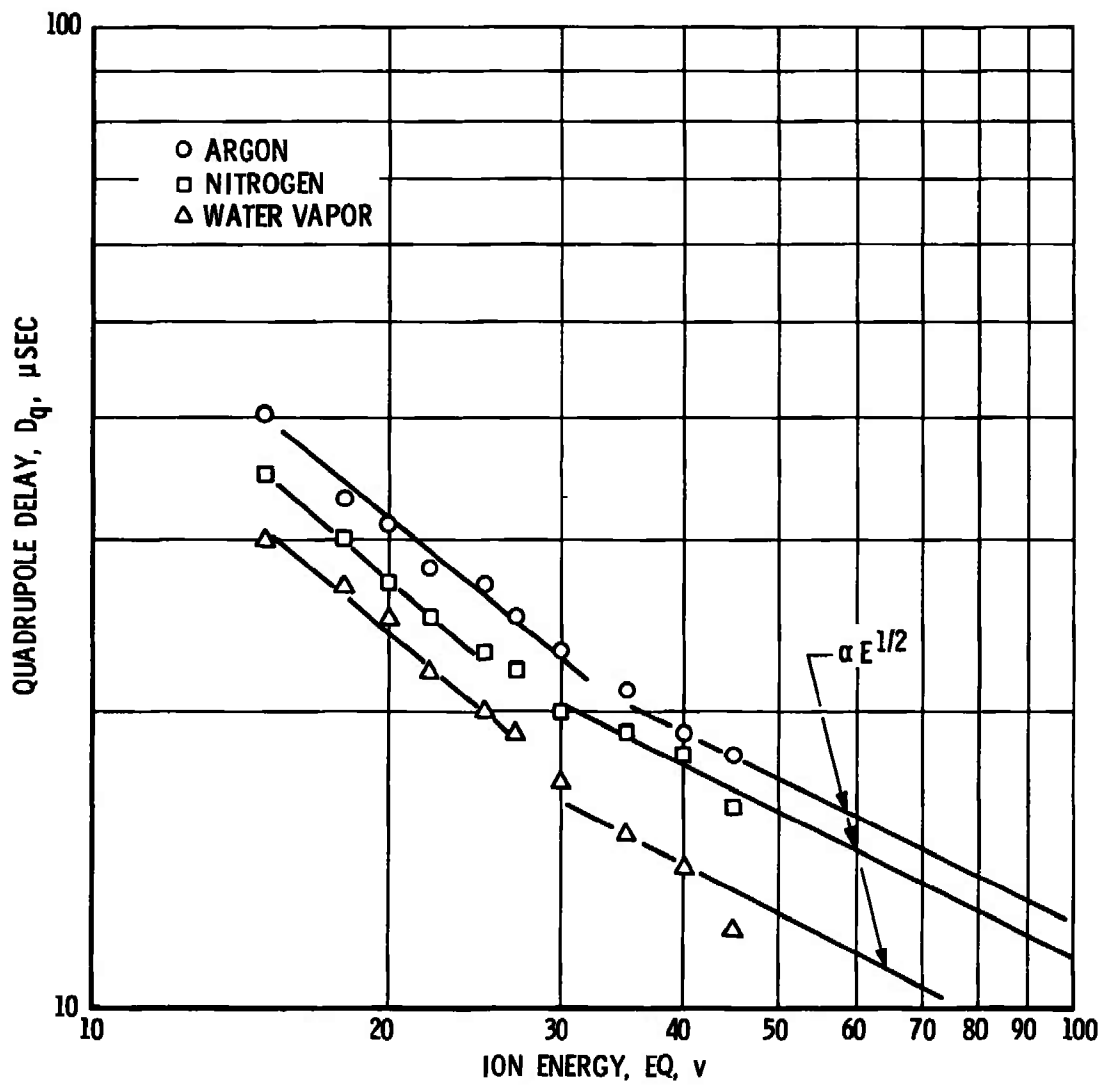


Fig. 8 Ion Flight Times in a Quadrupole Mass Spectrometer

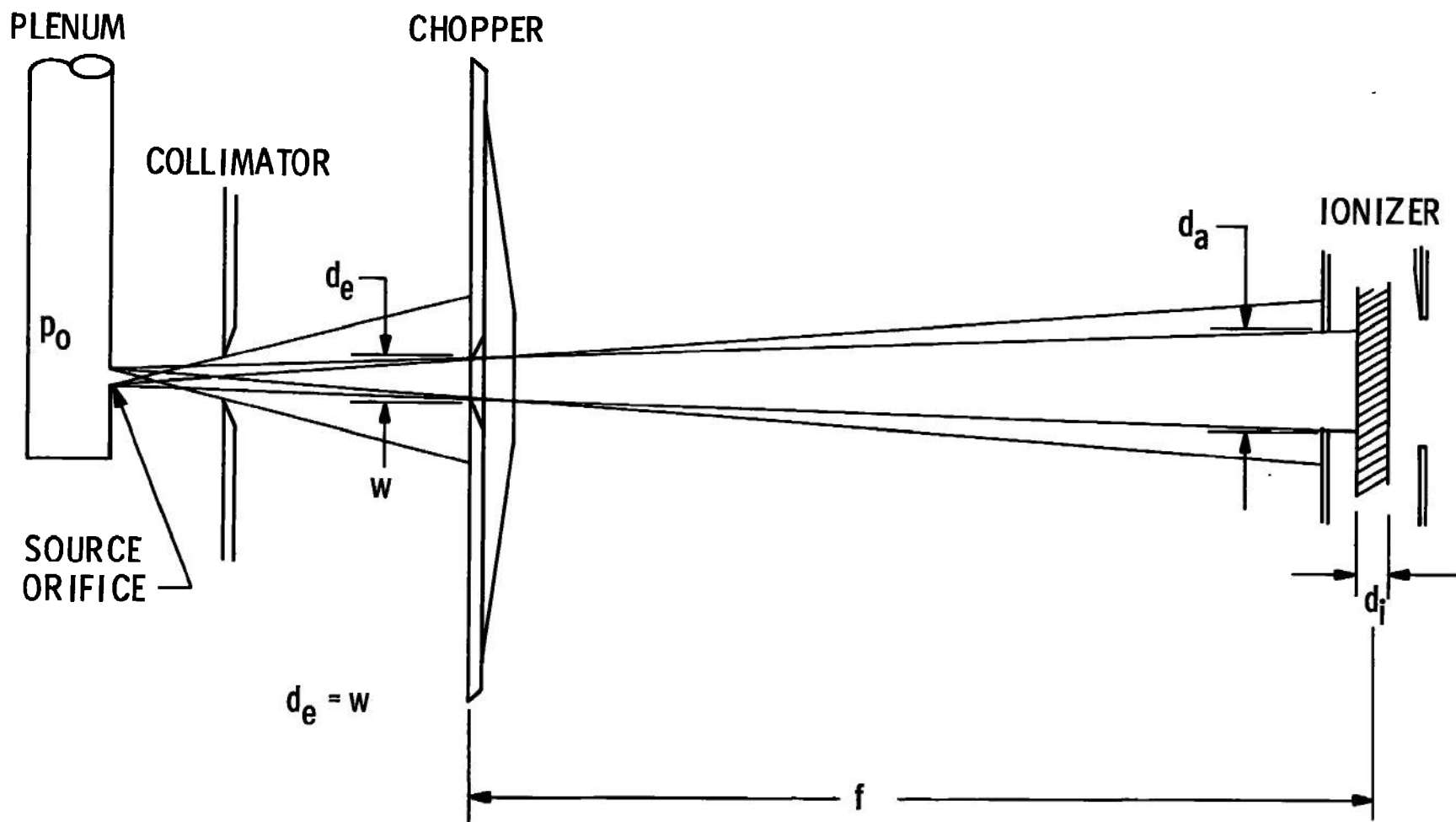
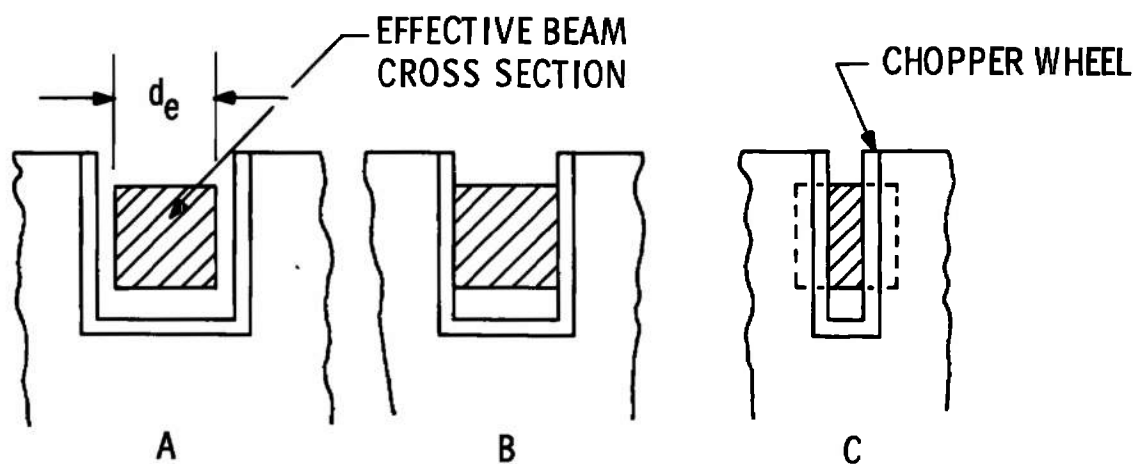


Fig. 9 Schematic of Molecular Beam System and Detector Cross Sections



$$\tau = \frac{2d_e S}{\pi D}$$

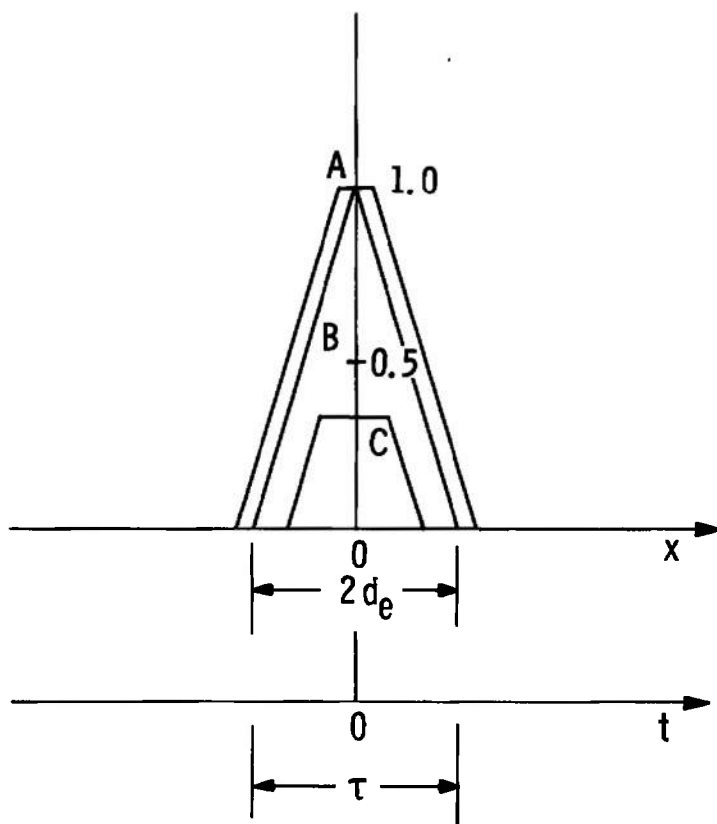


Fig. 10 Several Chopper Shutter Functions for Fixed Rotational Speed

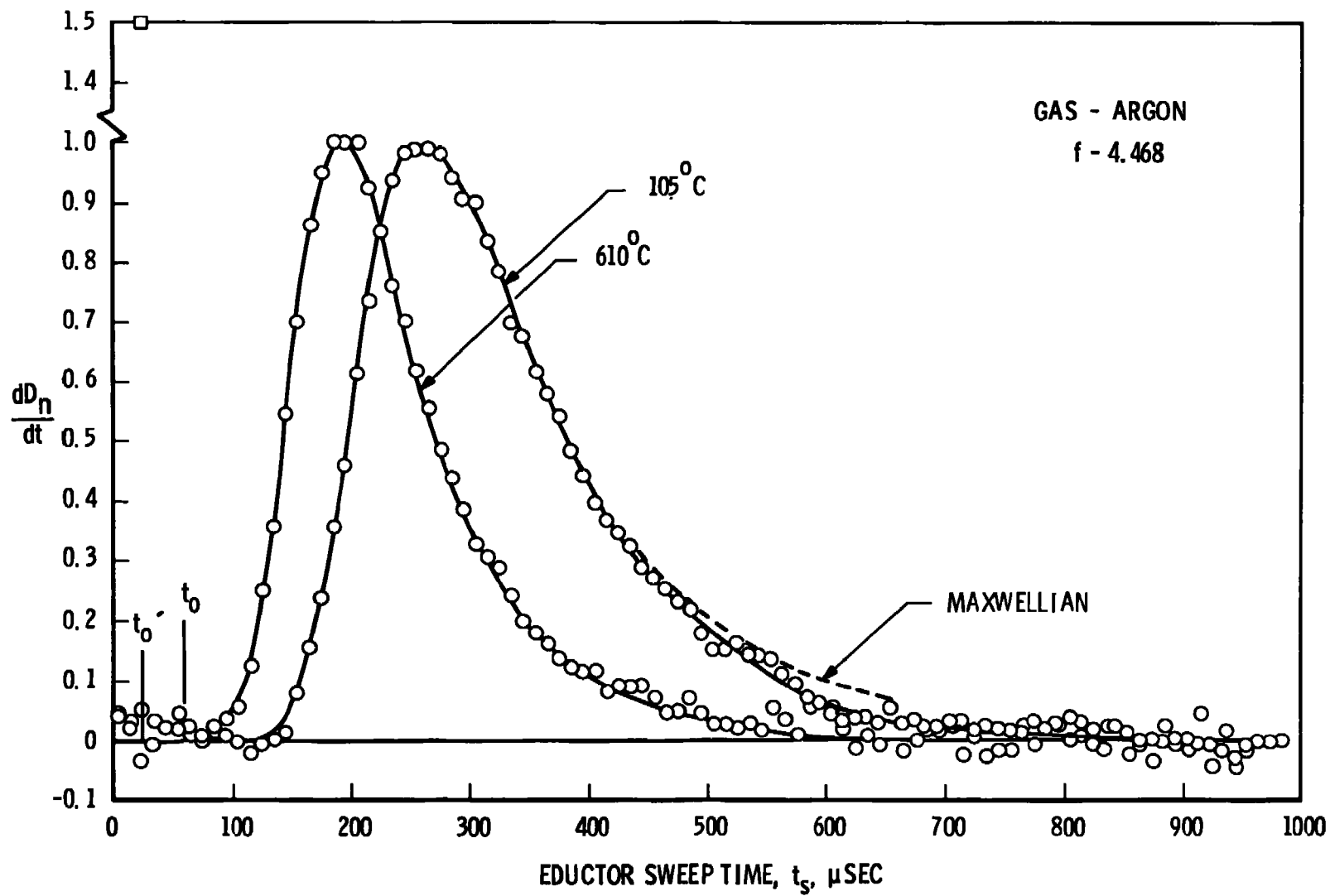


Fig. 11 Velocity Distributions for High Temperatures

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Arnold Engineering Development Center ARO, Inc., Operating Contractor Arnold Air Force Station, Tennessee		2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	
		2b. GROUP N/A	
3. REPORT TITLE A SYSTEM FOR THE MEASUREMENT OF VELOCITY DISTRIBUTIONS OF MOLECULAR BEAMS			
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) January 1 to December 1, 1967 - Final Report			
5. AUTHOR(S) (First name, middle initial, last name) H. M. Powell and J. H. Heald, Jr., ARO, Inc.			
6. REPORT DATE September 1968		7a. TOTAL NO. OF PAGES 34	7b. NO. OF REFS 4
8a. CONTRACT OR GRANT NO. F40600-69-C-0001		9a. ORIGINATOR'S REPORT NUMBER(S) AEDC-TR-68-151	
b. PROJECT NO 8951 and 4344			
c. Program Element Nos. 6144501F and 6540215F		9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) N/A	
d.			
10. DISTRIBUTION STATEMENT This document has been approved for public release and sale; its distribution is unlimited.			
11. SUPPLEMENTARY NOTES Available in DDC		12. SPONSORING MILITARY ACTIVITY Arnold Engineering Development Center, Air Force Systems Command Arnold Air Force Station, Tennessee	
13. ABSTRACT A system for determining the velocity distributions of molecular beams is described in this report. This system utilizes the time-of- flight technique whereby the velocities are inferred by measuring the flight time of the beam molecules over a known flight distance. A quadrupole mass spectrometer and signal averaging devices are used to improve the signal-to-noise ratio in such a way that the system is applicable to velocity measurements in an environment of a relatively high background gas density. The system is evaluated by comparison of measured distributions of beams obtained from an effusive source with equivalent calculated Maxwellian distributions. Agreement was good enough that the gas temperature could be calculated from the experi- mental data by using a least squares computer program. Distributions for beam densities down to 2.7×10^7 molecules/cm ³ in a total back- ground of 3.24×10^9 molecules/cm ³ were measured. The application of the system to studies involving gas-surface interactions and plume expansion processes from a nozzle is also discussed.			

14	KEY WORDS	LINK A		LINK B		LINK C	
		ROLE	WT	ROLE	WT	ROLE	WT
	velocity distributions molecular beams time-of-flight technique vacuum environments mass spectrometers signal-averaging devices						